Proceedings of the Ocean Optics XXI conference
Oct. 8-12, 2012 in Glasgow, Scotland

Vicarious Calibration Of The Hyperspectral Imager For Coastal Oceans (HICO) Using MOBY And AERONET-OC Data

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BACKGROUND

The Hyperspectral Imager for the Coastal Ocean (HICO) is housed on the International Space Station (ISS) and collects hyperspectral imagery for the study of the coastal ocean and adjacent lands. [1] Although HICO collects 128 contiguous spectral channels of solar reflectance in the 350 to 1070 nm wavelength range, the quantum efficiency of the sensor is best for the 86 channels in the 400 to 900 nm wavelength range. HICO can collect up to one scene per ISS orbit, which results in a maximum of 15 scenes per day. HICO was built and is managed by the United States Naval Research Laboratory (NRL).

Several data refinement transformations are required to generate standardized data products useful for research. These transformations are performed by the Remote Sensing and Oceanography Divisions of the Naval Research Laboratory, located in Washington, DC and at the Stennis Space Center, Mississippi, respectively. A sequence of software modules transforms HICO's raw data packets into ocean parameter data products. First, the raw data (Level 0) is calibrated and geolocated (Level 1B). Then the data is processed by the NRL-developed Automated Processing System (APS) to yield (Level 2) ocean products, such as chlorophyll concentration, absorption and backscattering coefficients, and other measurements.

Pre-launch characterization was performed on HICO in order to calibrate the sensor-measured top-of-the-atmosphere radiance (Lt) values. Factors such as the difference between laboratory environment and the space environment, vibrations on the sensor during launch, and degradation of the sensor over time in the space environment create the need for adjustments to the pre-launch characterization. Vicarious calibration applies a "reverse" atmospheric correction where satellite-derived atmospheric factors are added to in situ normalized-water-leaving radiances (nLw) to generate "vicarious" top-of-atmosphere radiances (vLt) that are then used to compute gain and offset values for each channel. [2] The gains and offsets are subsequently applied to the satellite sensor Lt values to force closer agreement with in situ measurements.

Traditionally, the Marine Optical Buoy (MOBY), moored near Lanai, Hawaii, has provided in-water measurements used in vicarious calibration for ocean color sensors. [3] In addition, in situ, above-water optical instruments have been added to some of the NASA AErosol RObotic NETwork platforms to perform Ocean Color measurements (AERONET-OC), thereby providing additional in-water measurements that can help to vicariously calibrate satellite data. [4]

APS automatically performs atmospheric correction and product generation for various earth-orbiting sensors. APS was modified to include a processing option which performs the vicarious calibration steps. A database of in situ MOBY and AERONET data has been compiled to provide in situ data coincident with satellite sensor overpasses. APS uses the in situ data to perform vicarious calibration

and generate new sensor gains and offsets. For accuracy assessment, these new gains and offsets are then applied to a separate set of HICO data with coincident in situ data. Error measurements taken before and after vicarious calibration are used to quantify the improvement in the satellite-retrieved nLw values.

METHODOLOGY

MOBY performs measurements of the atmosphere, Inherent Optical Properties (IOP) and nLw of water. MOBY has provided in situ data used in vicarious calibration of several NASA / NOAA sensors. The AERONET is managed by NASA Goddard Space Flight Center (GSFC). In addition to the over 500 locations that record atmospheric data, over 14 Ocean Color (OC) locations now also record in-water data including nLw values. The sites include areas near Venice, Italy, Long Island Sound, Martha's Vineyard, Chesapeake Bay, and the Gulf of Mexico. The SeaPrism sensors used in the AERONET network are recalibrated at regular intervals so that they maintain measurement accuracy.

APS is a collection of programs that automatically generates a co-registered image databases of geophysical parameters derived from remotely sensed data. APS has processed and currently processes data from multiple satellite sensors, including AVHRR, OCM, SeaWIFS, MERIS, and MODIS. It has been extended to process VIIRS and HICO data. After a Level 1B data file from any of the supported sensors arrives in the APS "incoming" directory, a program called "n2gen" processes the data to Level 2. During this process atmospheric correction is performed to generate nLw and remote sensing reflectance (Rrs) values. APS then generates all requested products, primarily from the Rrs spectra. There are various atmospheric correction algorithms available within APS. The Gordon-Wang atmospheric correction with the 80 aerosol models was selected for use in the current work.

The "n2gen" program has an "Inverse" mode which allows the user to specify in situ data for the point being processed. While the selected atmospheric correction is being performed various scattering and absorption factors are generated for use in adjusting the Lt value to derive the nLw value for each wavelength band. These include Rayleigh and aerosol scattering coefficients and atmospheric gas absorption coefficients. After the satellite-derived nLw values have been computed, the various scattering and absorption factors are still held in memory. If the "Inverse" mode has been set and in situ data have been provided, the satellite-derived nLw values are then replaced by the in situ nLw values. All the atmospheric correction scattering and absorption factors held in memory are then added to the in situ nLw values. This results in a vicarious top-of-the atmosphere radiance measurement, vLt, for each wavelength band.

The ratio of the vLt / Lt provides a vicariously calibrated gain factor that, when multiplied to the Lt value, provides the top-of the-atmosphere radiance value needed to derive the in situ nLw values as the satellite-derived nLw measurements. If multiple samples are used, a regression between the samples' Lt and vLt values can be used to generate vicariously calibration gain and offset values for each wavelength band. The samples can be processed again while using the newly computed gains and offsets. RMS errors can be generated between the new satellite-derived nLw values and the in situ nLw values and compared to RMS errors generated before the application of the new gains in order to assess the improvement in the measurement of nLw.

A SQL database for use in satellite sensor calibration / validation activity was created to hold the in situ data from MOBY and the AERONET SeaPrism sensors, as well as satellite data for various space-borne sensors. Standard SQL queries can be issues to extract nLw and other values from the database. These queries can be performed from software designed to automate the data extraction from the database. After being extracted from the database, the in situ nLw data can be used in vicarious calibration tasks.

Multiple samples for vicarious calibration can be drawn from various HICO scenes. Since HICO can acquire at most 1 scene per orbit and, in addition, there are other competing scenes for each ISS orbit, only roughly 35 scenes over MOBY have been acquired during the HICO lifetime. Similarly, the scenes over the AERONET sensors are limited. Furthermore, many of these scenes are contaminated by clouds. MOBY and AERONET HICO scenes were inspected visually to determine which were sufficiently free of clouds to be used in vicarious calibration.

The ISS orbit is another factor in realizing good matchups between the HICO and in situ data. HICO was installed on the ISS as a low-cost method for evaluating space-borne hyperspectral data collection and product generation. While having the sensor housed on the ISS has advantages, one limitation that it imposes is the lack of control over the overpass time and the repeat coverage of targets, which is completely dependent on the ISS orbit. In some cases, MOBY and AERONET HICO scenes were acquired very early in the morning or very late in the afternoon. Therefore, some HICO scenes were not acquired during a reasonable matchup time window with the MOBY and/or AERONET data collection.

While MOBY provides hyperspectral nLw values, the AERONET SeaPrism sensors provide multispectral nLw values. The HICO Lt values were convolved with MODIS spectral response function to generate a "MODIS-like" multispectral data set. This data set, termed HICO-MODIS, was vicariously calibrated using the AERONET sensor nLw values. So, while MOBY provides data for vicarious calibration of the full hyperspectral wavelength bands of HICO, the AERONET sensors provide data for vicarious calibration of the multispectral (HICO-MODIS) wavelength bands.

A software program called "Vical" was written to perform the vicarious calibration for HICO. It performs two passes; the first calibrates the near infrared (NIR) bands and the second calibrates the visible bands. The calibration of the NIR bands is performed separately because these bands contribute to the determination of the aerosol model used in the atmospheric correction. Any gains for the near-infrared bands need to be set first in order for the vicarious calibration of the visible bands to be stable.

For each of these passes, a list of HICO data files with the Level 1B Lt spectra is read. A threshold between the HICO and in situ data collection time is part of the data query to the calibration / validation database and, as a result, some queries may return without in situ data. If in situ data from the calibration / validation database is not available within a preset time of the HICO overpass, the sample is excluded from the process. If in situ data considered to be coincident with the HICO overpass is available, then it is returned from the calibration / validation database. The in situ data can also be read from a text file. This is useful if in situ data has been collected during a planned field campaign.

During this phase of the "vical" process, the "Inverse" mode of n2gen is set and the vLt values for the sample are generated using the in situ nLw values as previously described. Also, RMS error values

between the satellite-derived nLw and in situ nLw values are computed. This information is recorded to be used later in evaluating the improvement of the process.

After "Vical" generates the vLt for each of the samples, it performs a regression between the Lt and vLt values. The slope of the regression is used as the new gain and the y-intercept of the regression is used as the new offset through the equation:

Lt_new = (Lt * gain) + offset,
where Lt is the top of atmosphere radiance,
gain is the vicariously calibrated gain (slope),
offset if the vicariously calibrated offset (y-intercept),
and Lt_new is the vicariously calibrated Lt value

The samples are then reprocessed after adjusting the Lt values by the newly computed gains and offsets.

Alternatively, "vical" has the option of constraining the regression line to pass through the origin. This results in variable slope (gain) values with associated offsets of 0. This may seem to compromise the process by selecting results that do not minimize errors between the derived and in situ data. However, there are cases where the use of vicariously calibrated gains from regression forced through the origin provides for better adjustment when applied to scenes for targets at distances in time and place from the samples used in the calibration process. This could occur because the regression with variable y-intercept might over-fit the gains to a specific location with the y-intercept (offset) tightly constrained to the sample space. The vicarious gains from regression forced through the origin are much smoother from one contiguous wavelength band to the other. This dampens oscillations induced by potentially highly-variable offset values between contiguous wavelength bands. Although the generation of gains from regression between Lt and vLt which is forced through the origin continues to be explored, the results presented for the current work is limited to the unconstrained regression analysis.

RMS values are computed between the vicariously calibrated satellite-derived nLw and in situ nLw values. If the average RMS value for any particular sample is above a preset threshold, then that sample is removed from the sample set and a new epoch of the vicarious calibration process is performed without these samples. When an epoch completes without any samples being over the RMS value threshold, the process is considered to have converged.

The flagging of samples over several iterations is used as a filtering process to remove samples in scenes that might seem visually acceptable, but in actuality might be contaminated by atmospheric features such as haze or very thin clouds. Other criteria have been used to exclude samples in vicarious calibration of other sensors based on knowledge of proximity of clouds or other effects. However, the current work simply uses the RMS errors to flag any sample with results that stray significantly from the results of the rest of the samples.

The samples that remain in the final sample set are then broken into 2 groups; a training set and a test set. The vicarious calibration process described above is then rerun to generate gains and offsets from the training set. The newly computed gains and offsets are used to process the samples in the test set through the "n2gen" program in normal (non-inverse) mode. The RMS values between the newly-derived nLw values of the test set and the corresponding in situ nLw values are generated for each wavelength band. The difference in the RMS errors before and after the vicarious calibration is used to

evaluate improvements realized through vicarious calibration. These gains and offsets can then be applied to other scenes to vicariously calibrate each HICO scene that APS processes.

ANALYSIS / RESULTS

It is important to note that the vicarious calibration process adjusts the entire system that calculates the nLw values. This includes not only the recording of photons at the sensor and the originally calibrated Lt values, but also the atmospheric correction method used to process the data. In this work the Gordon-Wang atmospheric correction used within "n2gen" was selected to perform the atmospheric correction. The satellite-derived nLw values, and thereby the vicariously calibrated gains and offsets, may have different values when using other atmospheric correction algorithms. There are many other atmospheric correction algorithms, which include ATREM, ACORN, FLASH, TAFKAA, and Cloud / Shadow.

"Vical" was run using available HICO MOBY scenes and guidance from MOBY in situ data. A few scenes were excluded due to lack of concurrent MOBY data. Other scenes were excluded during the filtering process. There were 8 scenes in the final selection, which resulted in a training set of 4 scenes and a test set of 4 scenes.

Vicarious calibration using the 4 training set scenes provided new gains and offsets, which were then used to adjust the test set scenes' Lt values. Scatter plots of the in situ nLw and pre and post-vicariously calibrated nLw values for the 502 and 525 nmeter wavelength bands are shown in Figure I and Figure 2, respectively. The r^2 value for the scatter plots increased from 0.39 to 0.93 after the adjustment for the 502 nmeter wavelength band. The r^2 value for the scatter plots increased from 0.46 to 0.83 after the adjustment for the 525 nmeter wavelength band.

Graphs showing the in situ nLw spectral curve with the pre and post-vicariously calibrated nLw values for the test set dates are shown in Figures 3 and 4. The average of the RMS error across the HICO bands was computed for each sample. Then these "Sample" RMS errors were averaged across the four test set samples. The "Averaged Sample" nLw RMS error for the pre-vicariously calibrated test set was 0.85 radiance units. The "Averaged Sample" nLw RMS error for the post-vicariously calibrated test set was 0.23 radiance units.

"Vical" was also run using available HICO-MODIS AERONET scenes and guidance from AERONET in situ data. There are multiple AERONET sensors which can provide data for generating vicariously calibrated gains/offsets. Samples can also be aggregated from several or all the AERONET locations. Vicarious calibration results for only the Venice (AAOT) site are presented here.

For the Venice site a final set of 15 samples were selected, which resulted in 7 samples in the training set and 8 samples in the test set. A scatter plot of the in situ nLw and pre and post-vicariously calibrated nLw values for wavelength bands 488 and 547 are shown in Figure 5 and Figure 6, respectively. The r^2 value for the scatter plots increased from 0.35 to 0.59 after the adjustment for the 488 nmeter wavelength band. The r^2 value for the scatter plots increased from 0.62 to 0.76 after the adjustment for the 547 nmeter wavelength band.

Graphs showing the in situ nLw spectral curve with the pre and post-vicariously calibrated nLw values for the test set dates are shown in Figures 7 and 8. The "Averaged Sample" nLw RMS error for the

pre-vicariously calibrated test set was 0.39 radiance units. The "Averaged Sample" nLw RMS error for the post-vicariously calibrated test set was 0.29 radiance units.

CONCLUSIONS

The "vical" program incorporates a flexible process for performing vicarious calibration of HICO data. MOBY and AERONET in situ data were used in the vicarious calibration computation of gains and offsets for HICO and HICO-MODIS data. The new gains were applied to test sets of HICO data, producing improved satellite-derived nLw values. The r^2 values of the presented scatter plots between the sensor-derived nLw and in situ nLw increased after vicarious calibration for both the HICO and HICO-MODIS data sets.

RMS errors between in situ nLw values and the pre and post-calibrated nLw values were generated to provide assessments of the improvement realized through the vicarious calibration process. The "Averaged Sample" nLw RMS error for the HICO test data sets decreased from 0.85 to 0.23 radiance units after the vicarious adjustment. The "Averaged Sample" nLw RMS error for the HICO-MODIS test data sets decreased from 0.39 to 0.29 radiance units after the vicarious adjustment. Since vicarious calibration can provide sensor-derived nLw values that are more closely correlated with in situ nLw values and reduce the overall RMS error in data measurement, it proves to be a good method for fine-tuning the sensor calibration of the HICO and HICO-MODIS data sets.

ACKNOWLEDGEMENT

We acknowledge and appreciate funding from the Office of Naval Research (ONR) through the projects titled, "Hyperspectral Sensor Development for TACSAT" (Program Element: 0603758N) and "Improving Blended Multi-sensor Ocean Color Products through Assessment of Sensor Measurement Differences" (Program Element: 0602435N).

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APPENDIX A: FIGURES

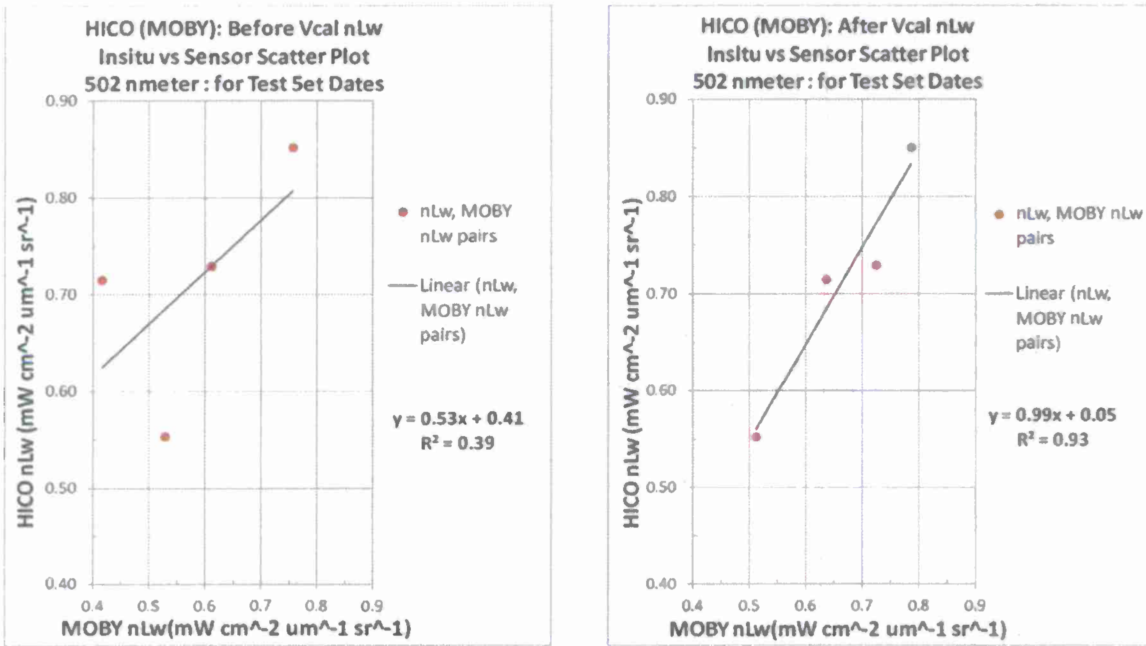

Figure 1. Scatter plot of MOBY in situ and HICO nLw values at 502 nm wavelength before and after vicarious calibration

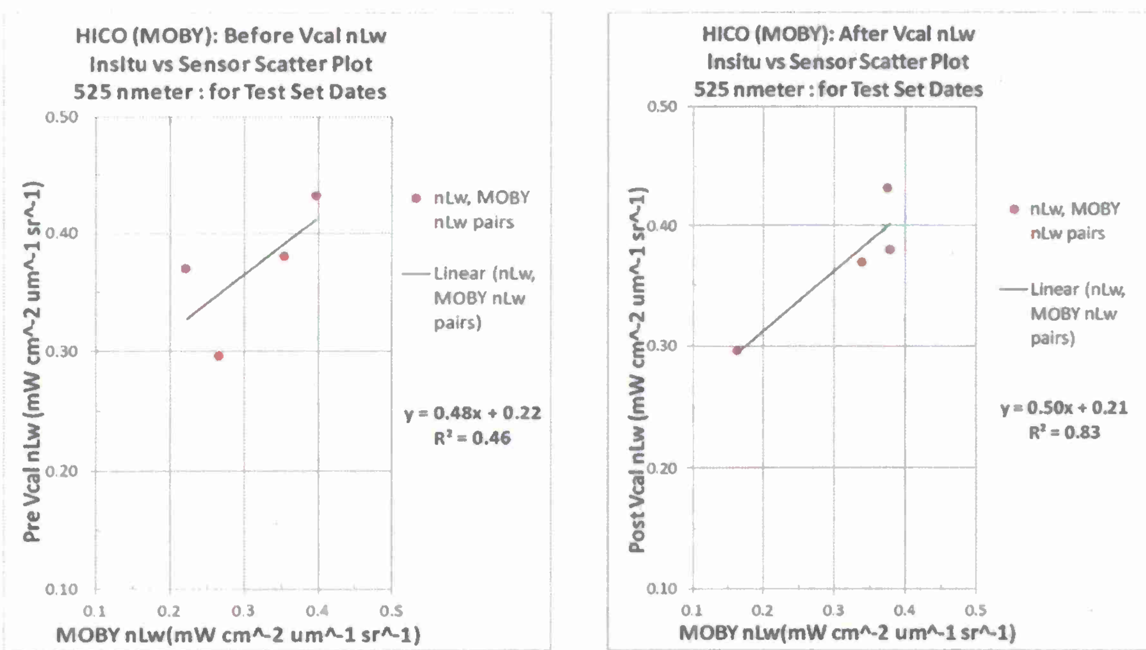

Figure 2. Scatter plot of MOBY in situ and HICO nLw values at 525 nm wavelength before and after vicarious calibration

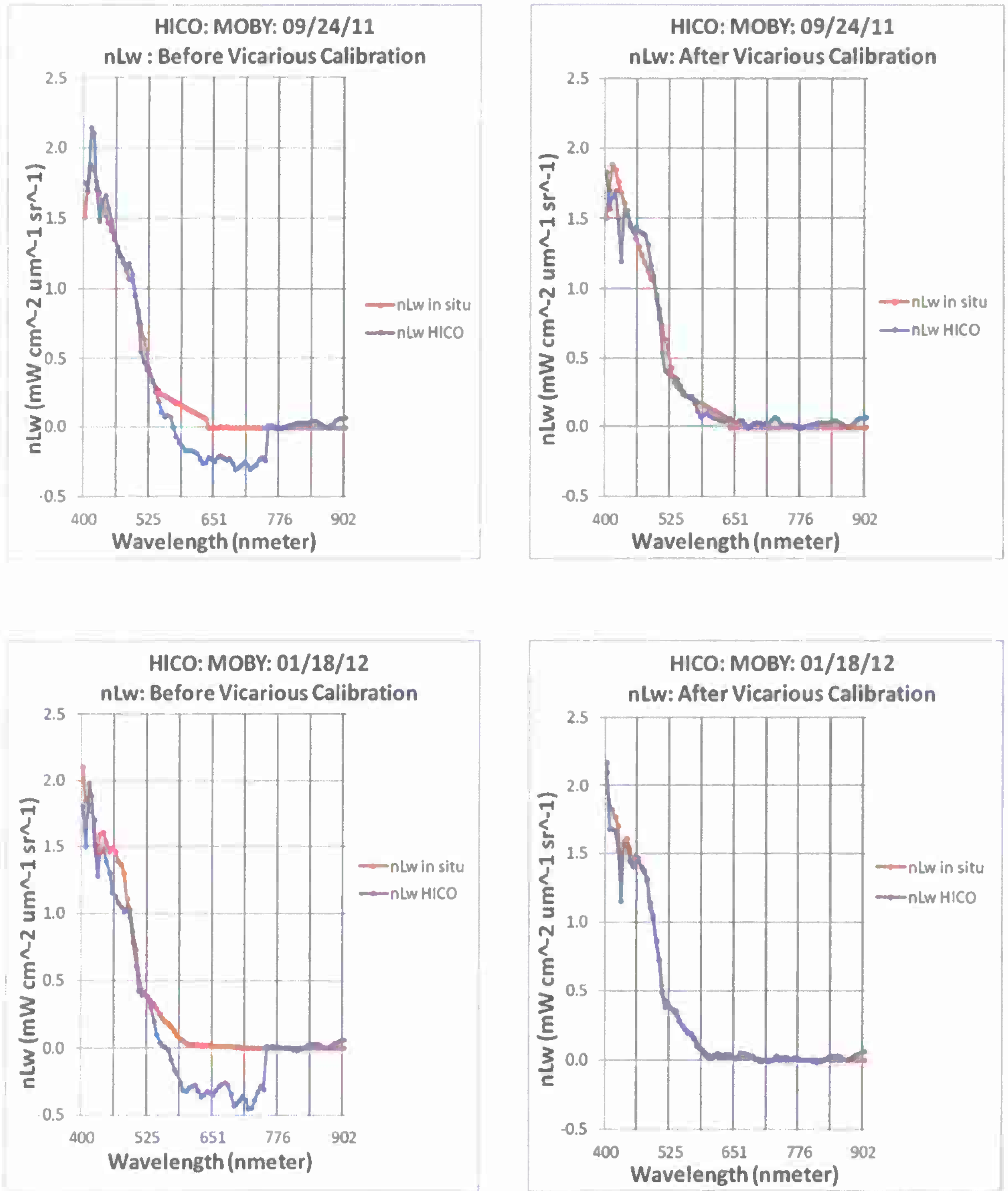

Figure 3. MOBY In situ nLw spectral curve with HICO nLw spectral curve before and after vicarious calibration for 09/24/11 and 01/18/12

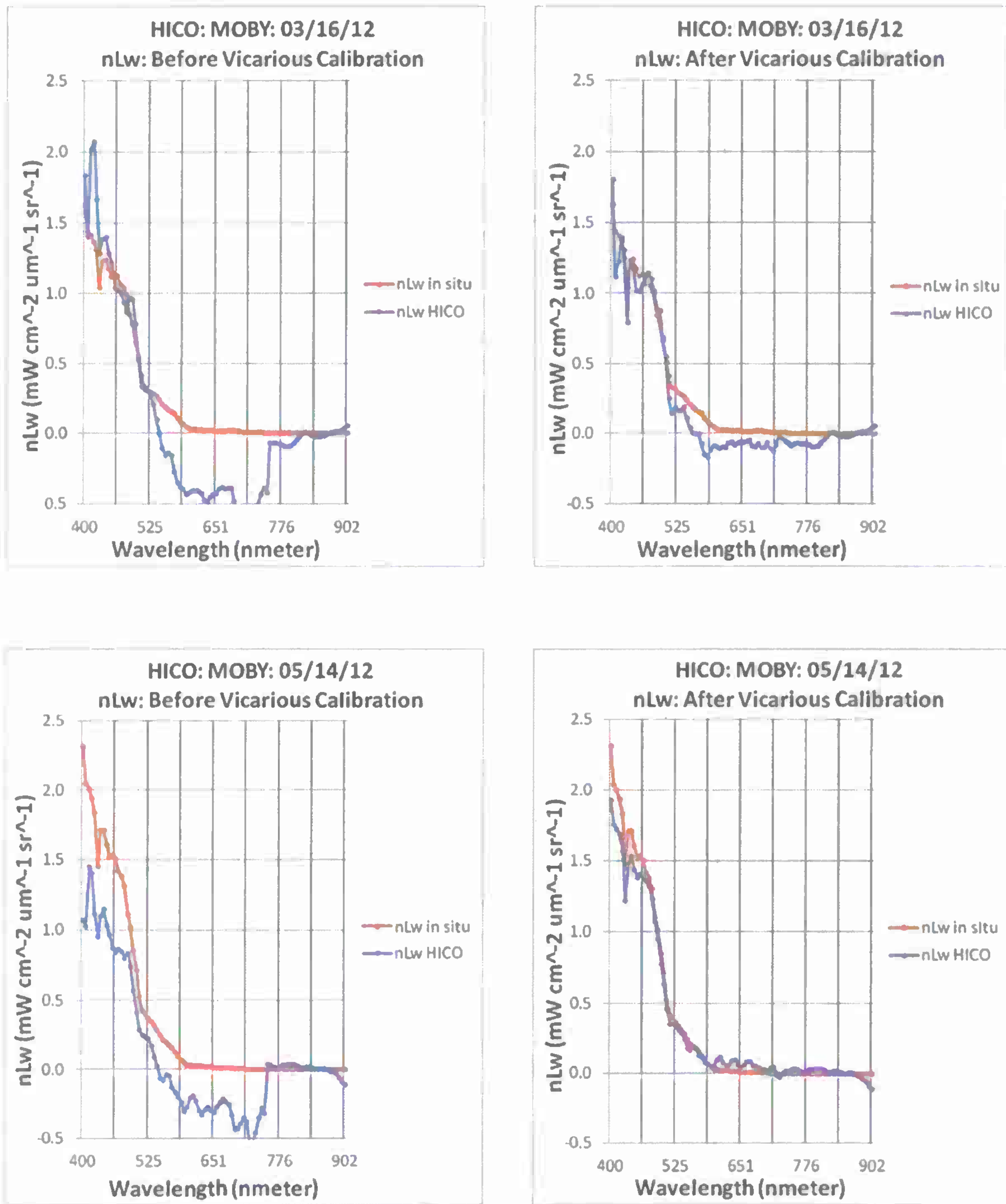

Figure 4. MOBY In situ nLw spectral curve with HICO nLw spectral curve before and after vicarious calibration for 03/16/12 and 05/14/12

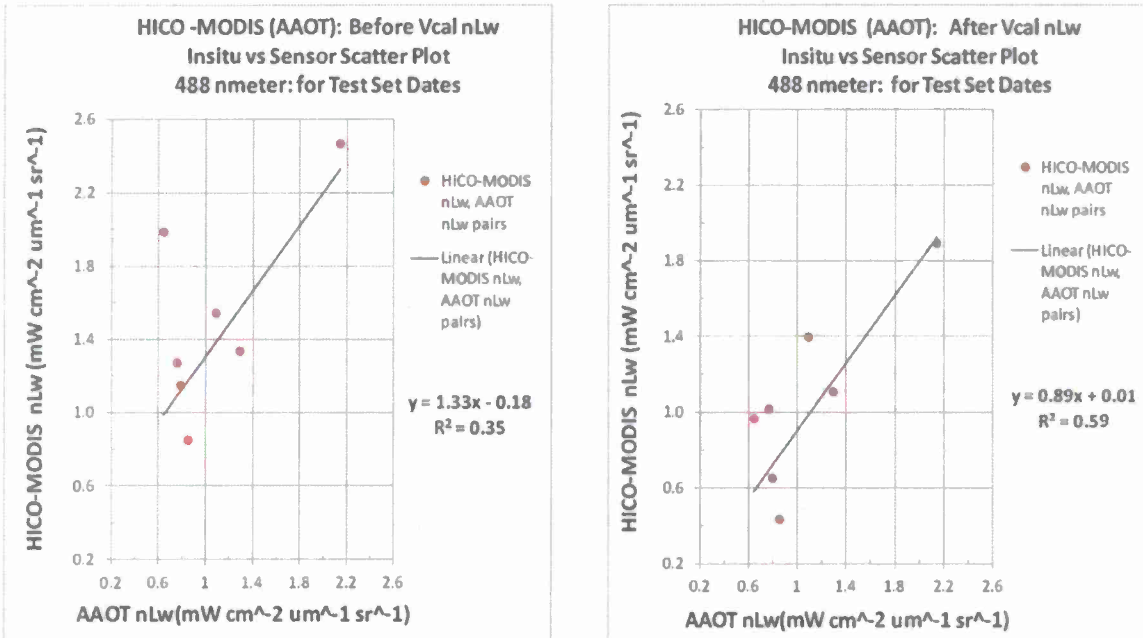

Figure 5. Scatter plot of AAOT in situ and HICO-MODIS nLw values at 488nm wavelength before and after vicarious calibration

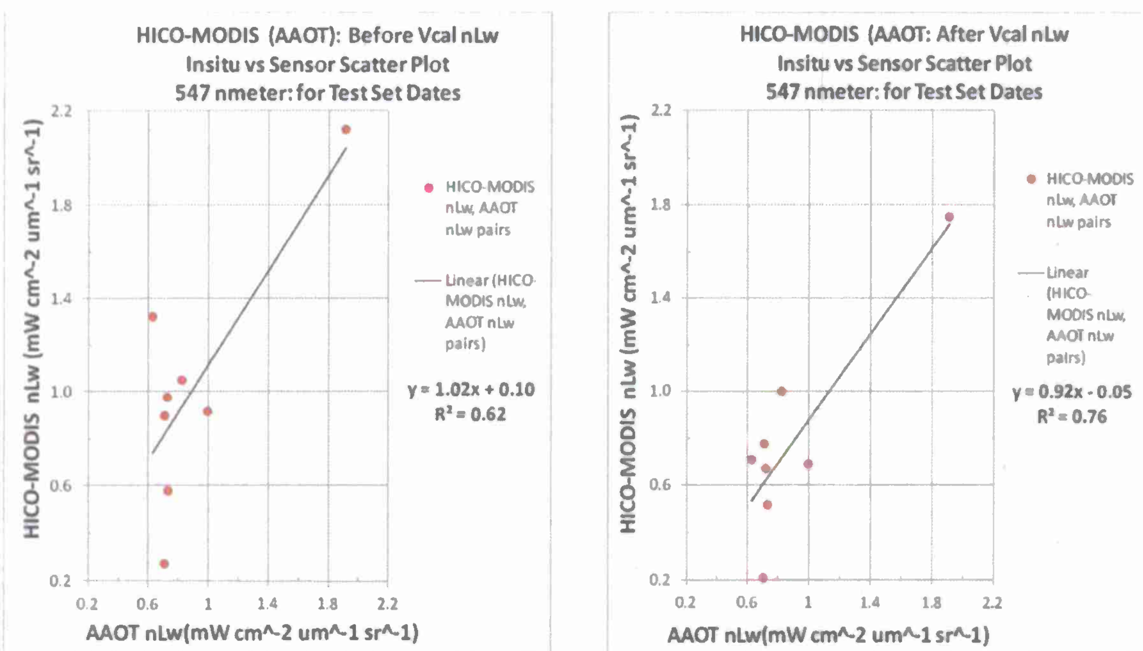

Figure 6. Scatter plot of AAOT in situ and HICO-MODIS nLw values at 547 nm wavelength before and after vicarious calibration

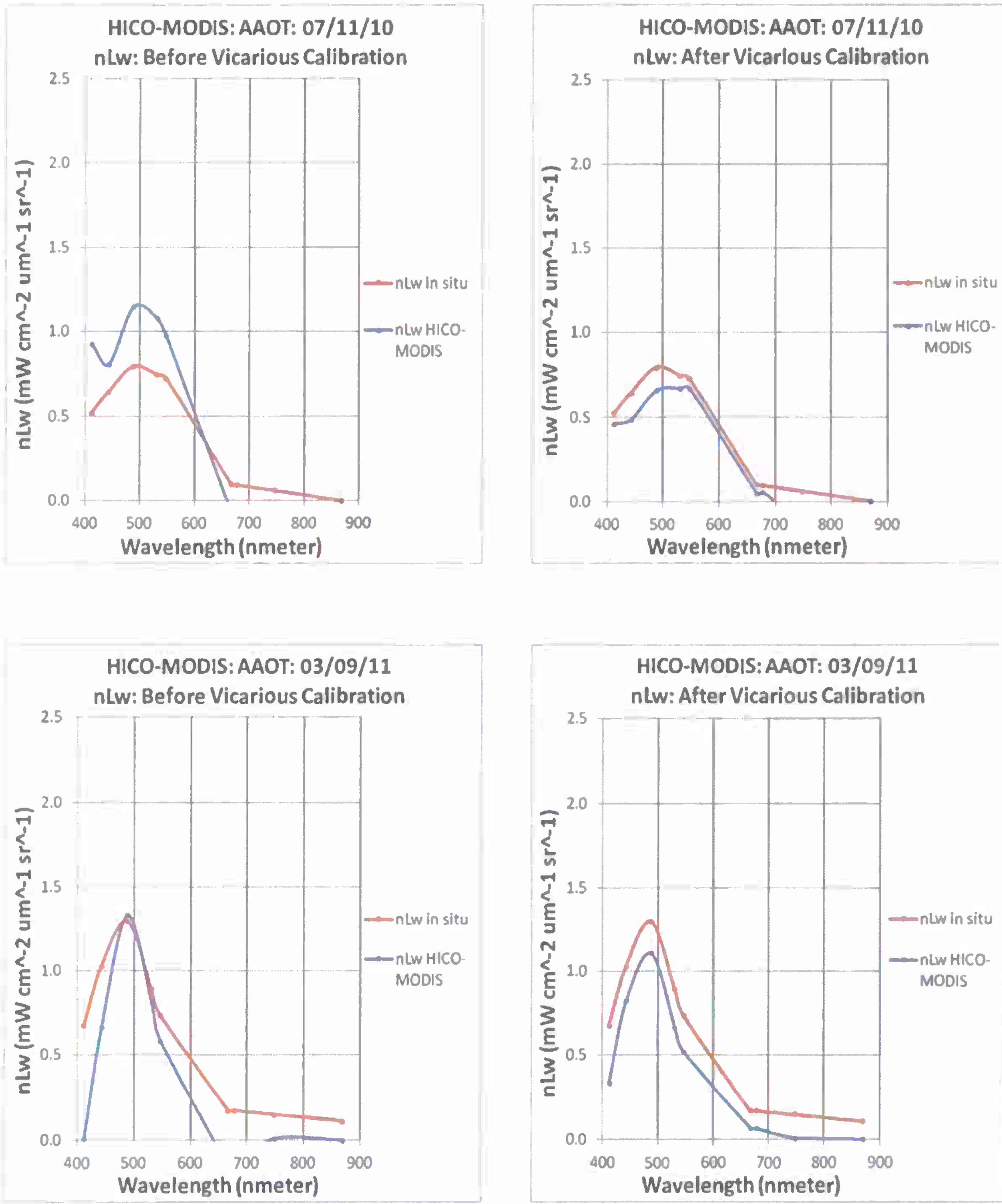

Figure 7. AAOT In situ nLw spectral curve with HICO-MODIS nLw spectral curve before and after vicarious calibration for 07/11/10 and 03/09/11

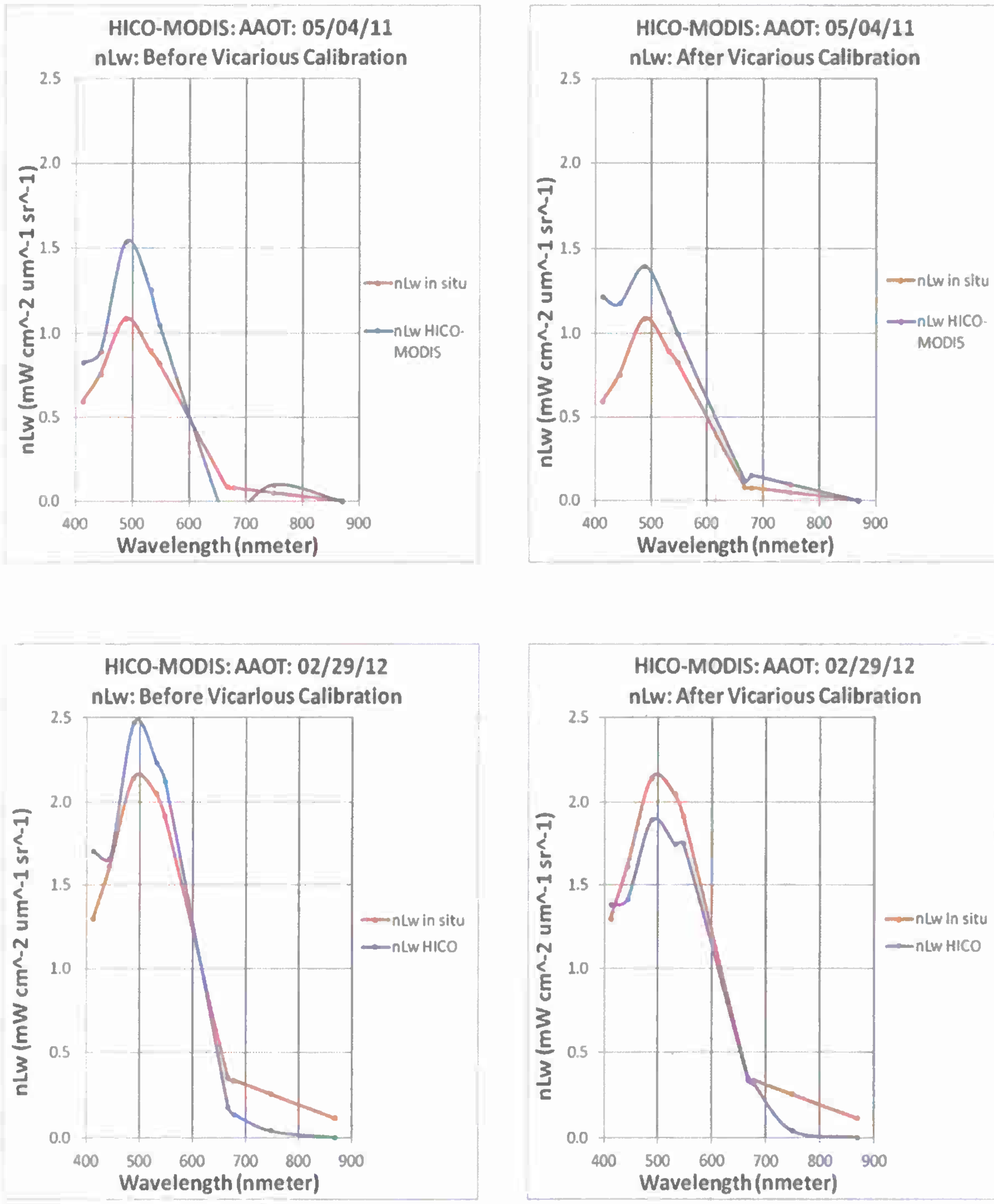

Figure 8. AAOT In situ nLw spectral curve with HICO-MODIS nLw spectral curve before and after vicarious calibration for 05/04/11 and 02/29/12

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05-12-2012	Conference Proceeding	

4. TITLE AND SUBTITLE	
Vicarious Calibration of the Hyperspectral Imager for Coastal Oceans (HICO) Using MOBY and AERONET-OC Data	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 0602435N
6. AUTHOR(S) David Lewis, Richard W. Gould, Sherwin D. Ladner, Timothy Adam Lawson and Paul Martinolich	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 73-6552-02-5

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Naval Research Laboratory Oceanography Division Stennis Space Center, MS 39529-5004	NRL/PP/7330--12-1391

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Office of Naval Research One Liberty Center 875 North Randolph Street, Suite 1425 Arlington, VA 22203-1995	ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Hyperspectral Imager for Coastal Oceans (HICO) was constructed and is managed by the US Naval Research Laboratory (NRL). Pre-launch calibration, and therefore sensor measurement accuracy, of satellite sensors can be affected by launch vibrations, temperature fluctuations, space radiation and other factors. Vicarious correction was applied to HICO imagery to improve measurement accuracy. Vicarious calibration applies a "reverse" atmospheric correction where satellite-derived atmospheric factors are added to in situ normalized-water-leaving radiances to generate "vicarious" top-of-atmosphere radiances that are used to compute gain and offset values. The gains and offsets are subsequently applied to satellite sensor top-of-atmosphere radiances to force closer agreement with in situ measurements. In situ data from the Marine Optical Buoy (MOBY) and from some of the NASA AErosol RObotic NET Ocean Color (AEONET-OC) platforms were used to provide in situ water measurements used to vicariously calibrate HICO data.

15. SUBJECT TERMS

HICO, vicarious calibration, MOBY, AERONET

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					David Lewis
Unclassified	Unclassified	Unclassified	UU	12	19b. TELEPHONE NUMBER *(Include area code)* 228-688-5280